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Araştırma Makalesi / Research Article

Investigation of Fluid Flow Through the Ureteral Canal with A Porous Media Approach in the Ureteral Stone Reduction Process

Merdin DANIŞMAZ[1*]

Abstract

This study includes the examination of the stone removal process by computational fluid dynamics analysis in the kidney and ureteral canal, which is modeled as the fluid evacuation channel for the urine flow. SolidWorks 2020 R2 commercial software was used for three-dimensional modeling and Flow Simulation plugin for flow simulation analysis. The kidney with the size of 12x6x6cm and in addition to this, the ureteral canal with the largest internal diameter of 20 mm (at the kidney outlet) and the smallest diameter of 5 mm (at the canal outlet) were modeled. Pressure distribution in the presence of flow was determined in case of stone stuck in the middle part of the ureteral canal. To identify the partially occluded region allowing flow, the kidney stone region was defined as a porous medium for analysis. Four different conditions (between 0.90 and 0.99) for permeability in this region were included in the analysis to represent stone size and structure. The change in pressure-velocity distribution and its effect in the kidney area were seen at 5 different entry speeds. The effect of different permeability conditions on the pressure difference was shown graphically. The findings showed the presence of high pressure (peak 1850 mmH_2O) throughout the flow volume at narrow passages and low permeability conditions, as expected. At 90% permeability, the maximum local velocity in the blockage zone was found to be 4.5 m/s and this value tends to decrease with increasing permeability. It was predicted that the pressure-velocity relationship along the flow can provide information on treatment and intervention, depending on the stone and canal structure whose properties are predetermined. It was concluded that a preliminary idea could be formed about the extent of pain due to high pressure, especially for the stone dropping process, which does not cause complete obstruction in the canal and is defined as a porous medium in this analysis.

Keywords: Kidney and ureteral stones, Flow in the ureteral canal, Kidney stone removal, CFD

Böbrek Taşı Düşürme İşleminde Üretral Kanal İçindeki Akışkan Akışının Gözenekli Ortam Yaklaşımı ile İncelenmesi

Öz

Bu çalışmada, idrar akışında akışkan tahliye kanalı olarak modellenen böbrek ve üreter kanaldaki taş düşürme işleminin hesaplamalı akışkanlar dinamiğiyle (HAD) analizi ile irdelemesini yapıldı. Üç boyutlu modelleme için SolidWorks 2020 R2 ticari yazılımı ve akış simülasyon analizi için Flow Simulation eklentisi kullanıldı. 12x6x6cm boyutlarında böbrek ve buna ek olarak en büyük iç çapı 20 mm (böbrek çıkışında) ve en küçük çapı 5 mm (kanal çıkışında) olan üreter kanalı modellendi. Üreter kanalının orta kısmına taş sıkışması halinde akışın varlığında basınç dağılımı belirlendi. Akışa izin veren kısmen tıkalı bölgeyi belirlemek için, böbrek taşı bölgesi analiz için gözenekli bir ortam olarak tanımlandı. Bu bölgedeki geçirgenlik için dört farklı koşul (0.90 ile 0,99 arasında) taş boyutunu ve yapısını temsil etmek üzere analize dahil edildi. Basınç-hız dağılımındaki değişim ve bunun böbrek bölgesindeki etkisi 5 farklı giriş hızı için belirlendi. Farklı geçirgenlik koşullarının basınç farkına etkisi grafiksel olarak gösterildi. Bulgular, beklendiği gibi dar geçişlerde ve düşük geçirgenlik koşullarında akış hacmi boyunca yüksek basıncın (pik değer 1850 mmH_2O) varlığını gösterdi. %90 geçirgenlik oranında tıkanma bölgesinde maksimum lokal hız 4.5 m/s olarak bulundu ve geçirgenlik artışıyla birlikte bu değer azalma eğilimindedir. Akış boyunca basınç-hız ilişkisinin, özellikleri önceden belirlenmiş olan taş ve kanal yapısına bağlı olarak tedavi ve müdahale hakkında bilgi verebileceği öngörüldü. Özellikle kanalda tam tıkanmaya neden olmayan ve bu analizde gözenekli bir ortam olarak tanımlanan taş düşürme işlemi için yüksek basınca bağlı ağrının boyutu hakkında fikir oluşturulabileceği kanısına varıldı.

Anahtar Kelimeler: Böbrek ve üreter taşı, Üretral kanalda akış, Böbrek taşı düşürme, HAD

[1]Kırşehir Ahi Evran University, Mechanical Engineering Department, Kırşehir, Türkiye, m.danismaz@ahievran.edu.tr

[1]https://orcid.org/0000-0003-2077-9237

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1. Introduction

The human body is equipped with channels and vessels and works like a multifunctional mechanical installation. Much flow research in mechanical engineering deals with flow through constricted pipes and its application to various human body circulatory systems. It is useful to model these systems and analyze them with computerized calculations. CFD models have been applied to the circulatory system in a variety of ways, including flow effects in vasoconstriction and variable types of blood flow. In the vein wall over the years, smoking, cholesterol, etc. Mechanical examination of arterial disturbances caused by plaques that develop due to factors are included in these studies. CFD analysis has even been evaluated in fluid mechanics in the respiratory system and digestive system in relation to flow simulation and analysis. For example, a study by Caruso et al. performed a computational fluid dynamics comparison between different outlet graft anastomosis locations of the left ventricular assist device in a patient-specific aortic model (Caruso et al., 2015). Singla et al. presented a new approach in the diagnosis of urinary tract obstruction using HAD analysis (Singla et al., 2008). In the study, various hypothetical models were created in the Gambit program, in which flow physics was evaluated according to changing geometries and conditions. These models showed short segments of contraction and possible effects of occlusion. Flow analysis was performed by comparing velocity, static pressure, dynamic pressure, total pressure, and wall shear stress contours with the results predicted by flow theory with Fluent software. Another study (Carniel, 2021) aimed to demonstrate the potential of computational bioengineering in the field of lower urinary tract pathophysiology. It has been stated that engineering methods allow the investigation of urine flow in healthy and pathological conditions and analysis of urethral obstruction through artificial urine effects. Computational models of the bladder and urethra have been developed and investigated lower urinary tract physiology in health and disease. As a result of the study, it is stated that bioengineering methods will allow to expand and deepen the knowledge about lower urinary tract functionality. In more detail, it is concluded that modeling techniques provide information that contributes to explaining the occurrence of pathological conditions and will allow for the design and optimization of clinical-surgical procedures and devices. Numerical analysis of deformation and flow in the proximal region of the urethra was studied by research group (Mackiewicz, 2020). As a result of the study, a geometric and numerical model of the urethra was developed based on histological photographs. The urethra was tested in a flat deformation condition. Stress and stress fields of the Caucha tensor were investigated. A methodology for testing the dynamics of urine flow in the highly deformable urethra was proposed.

Urinary tract obstruction is a common clinical problem involving narrowing of the ureters or urethra. Current diagnostic methods are costly, and urologists are constantly looking for new, inexpensive, non-invasive measures to diagnose obstruction. Stones that do not obstruct the kidney canal (ureter) do not cause any symptoms or signs, with the exception of hematuria (Resnick, 2004). This form of flow can be thought of as the natural flow of urine. However, if the stone blocks the ureteral area, the pain is localized to the kidney. One of the main causes of pain is the formation of high pressure in the kidney region as a result of the obstruction of the ureteral canal, which we will describe as the flow channel. As the stone moves down the ureter, the pain moves down and towards the front of the body. In this case, the pressure areas change, and the stone moves through the channel without removing the obstruction. Stones less than 5 mm in diameter have a high chance of passing through the ureter; Those 5-7 mm have an average chance of expulsion (50%), and those larger than 7 mm almost always require urological intervention (Coe & Worcester, 2005).

2. Materials and Methods

The stone dropping process is schematically given in Figure 1. The shapes of kidney stones are mostly not smooth-surfaced. The urine flow continues partially thanks to the cavities and protrusions on the surface of the stone that block the channel due to its dimensions.

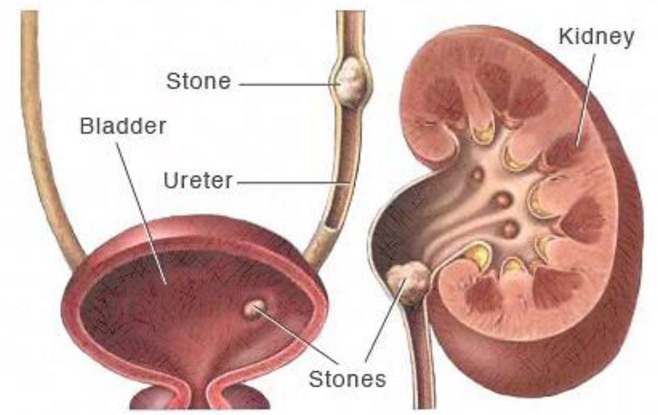

Figure 1. Stone reduction/dropping process (schematic) (Mayo, 2023)

The ureteral canal has the ability to stretch. Considering this situation, it differs from the standard channel flow. In many engineering applications, the channel geometry is designed as rigid and the deformation of the fluid pressure on the surfaces can be tolerated by the right material selection. The effects that cause shape change are not within the scope of this subject. Although kidney and ureteral stones do not have a definite shape, the number of stone removal processes in which there is a flow is quite large. In this study, the ureteral canal was considered as an elliptical and rigid canal. An example ureteral stone is given in Figure 2. For this process, how much of the flow is allowed to pass is more important than the shape of the stone. It is possible to model a porous environment by determining a stone region that blocks the channel and does not move. Thus, the porosity conditions will give an idea about the pressure changes in the kidney and canal region. This study includes exactly such a flow analysis. What makes the study useful is that computational fluid dynamics (CFD) is one of the rare studies that helps diagnostic applications of flow in the urinary system. (Constante-Amores et al., 2023)

Figure 2. Ureteral stone (Allen, 2023)

2.1. Modeling and Assumptions

In the stone removal process, kidney, ureteral canal, and stone form the basic elements of modeling. First, a 3D control volume model was created. Figure 3a and Figure 3b show the kidney-ureter modeling and the occluded stone region, respectively. The overall dimensions of the kidney were determined as 60x120x30mm. Just at the exit of the kidney, the ureteral canal begins with a 30 mm circular section. In the first quarter of the total canal length, the cross-section diameter changes rapidly and decreases to 10 mm. Subsequent section narrowing changes linearly and the ureteral outlet section diameter decreases to 5 mm. Due to the nature of the stone, the zone where the kidney stone is stuck can be considered as a porous media that completely covers a certain volume of the ureteral canal. In the analysis, this zone was selected in the middle section to see the flow inlet and outlet effects together. The inlet section represents the velocity inlet, and the outlet section represents the pressure outlet. With this determined velocity input, fluid flow is provided in the negative y direction. This model was then simulated in Flow Simulation. Only the fluid pressure and velocity relationship were considered in the modeling of the stone dropping process.

The effect of varying the distance between different constriction sections along the channel was initially observed by considering several different distance situations. However, the effect of permeability in the occlusion zone was observed to be more effective, and the occlusion zone model was fixed at an average narrowing section. In mildly and severely constricted models, the effect of constriction intensity is related to stone size and shows similar flow behavior. The channel section is designed as elliptical. Both narrowing depth and width are taken into account. The permeability of the porous media characterizing the clogging was tested with random values from 0.01 to 0.99. The highest permeability condition represents the flow without complete obstruction.

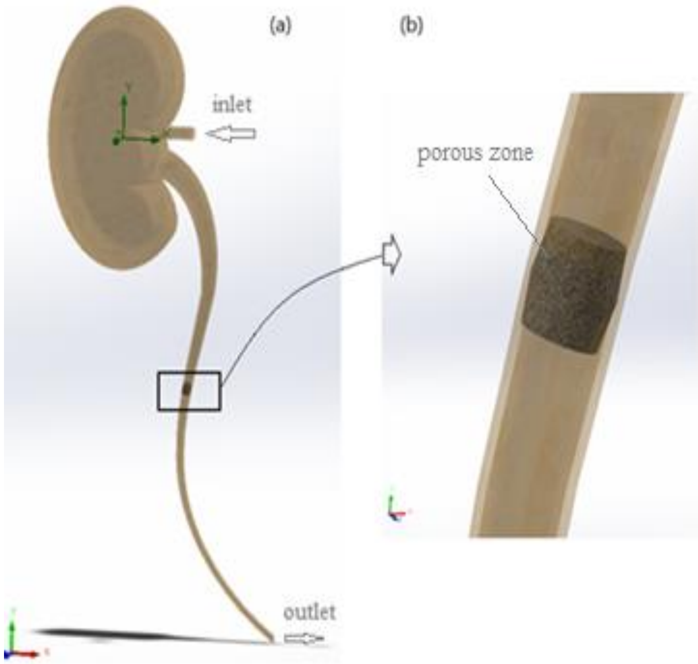

Figure 3. Modeling of ureteral occlusion a) Kidney and ureter b) Blockage zone

It should be noted that many factors, from body functions to the characteristics of the disease, must be considered in detail in order to model the process as a whole. Continuous and incompressible flow conditions are some of the assumptions in this basic approach.

2.2. Governing Equations

The hypothetical ureteral canal model presented the narrowing segments of the urinary tract and possible geometric representations of stone-induced obstruction. In this model, more emphasis has been placed on evaluating the physics and dynamics of flow based on variable geometries and boundary conditions. The Reynolds number for all simulated models was changed and simulated again using the appropriate flow solver. Flow behaviors were compared for Reynolds values between 120 and 1205. Input velocities were calculated using Equation 1, respectively, at values ranging from 0.101 to 1 m/s. The Reynolds number (Re) defined in Equation 1 is used to determine whether the flow is laminar (usually $Re < 2300$ for internal flow), turbulent internal flow for $Re > 4000$, or transitive flow for intermediate values. Since Re is only an approximation, the determination of turbulence depends on other factors such as geometric complexity.

$$Re = \frac{u_m D_h}{\vartheta} = \frac{\rho u_m D_h}{\mu} \quad (1)$$

Here, ρ is the urine density. During the stone removal process, this value will also change depending on the blood content (1002-1035 kg/m^3). In this analysis, the density was chosen as 1017 kg/m^3. In a study by a team (Inman et al., 2013), estimates of urinary kinematic viscosity as a function of moderate sunstroke state and temperature in a variety of common clinical conditions were used for treatment planning for bladder diseases. In conclusion, they stated that the kinematic viscosity of urine is always higher (about 10% higher) than pure water in the range of 20–42°C. The kinematic viscosity of urine decreases with increasing temperature, and its specific gravity is not a substitute for the kinematic viscosity of urine. In this study, the kinematic viscosity of urine was taken as 0.83x10-6 m^2/s for a density of 1017 kg/m^3 and a temperature of 37 °C.

Each flow model has been developed as porous media to be applied more precisely for stone flow that remains blocked in the human urinary tract.

This flow pattern represents the flow of the fluid filled into a tank in a narrowing section through a channel. Pressure and velocity distributions conform to the Bernoulli flow principle given in Equation 2, which is based on the pressure-velocity relationship (Stelmashuk & Tugolukov, 2020)).

$$\frac{P}{\rho} + \frac{V^2}{2} + gz = constant \quad (2)$$

The urine used in modeling is a Newtonian fluid in which there is a simple, linear relationship between shear stress and velocity gradient. Viscous, incompressible Newtonian fluids are governed by the Navier-Stokes equations. In these equations, u_i (i = 1,2,3) the three components of velocity, fi fundamental forces (such as gravity), p pressure, and μ the constant viscosity of the fluid (Ravi et al., 2022). Since the viscosity and density of the working fluid were treated as a constant, such equations could be applied as follows:

Continuity equation:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (3)$$

Momentum equation:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \quad (4)$$

Energy equation:

$$\frac{\partial}{\partial x_j}\left(\rho u_j C_p T - k\frac{\partial T}{\partial x_j}\right) = 0 \tag{5}$$

The standard k-epsilon (k-w) model was used to evaluate turbulent flow. This model is suitable for turbulent flows where molecular viscosity is unimportant. The solvent was chosen because it is one of the most practical and essential solvents for engineering goals and CFD applications.

3. Findings and Discussion

3.1. Mesh independence test

In flow analysis, it is necessary to detect that the solver obtains values independent of the number of cells. To ensure consistency in models, it is important to perform a grid independence test for all 3D situations as the finer grid structure provides greater accuracy. Such a test reduces the network range to such a point that further reduction of the range minimizes time and memory consumption. In addition, analysis outputs will emerge that have a negligible effect on the result of the simulation. In order to maintain the accuracy of the flow and the sensitivity of the porous environment conditions, smaller cellular fragmentation was also performed for the stone and its region, thanks to local grating. This situation is given in Figures 4.a and 4.b. Flow Simulation plug-in of SolidWorks software was used for drawing and analysis (SolidWorks, 2020).

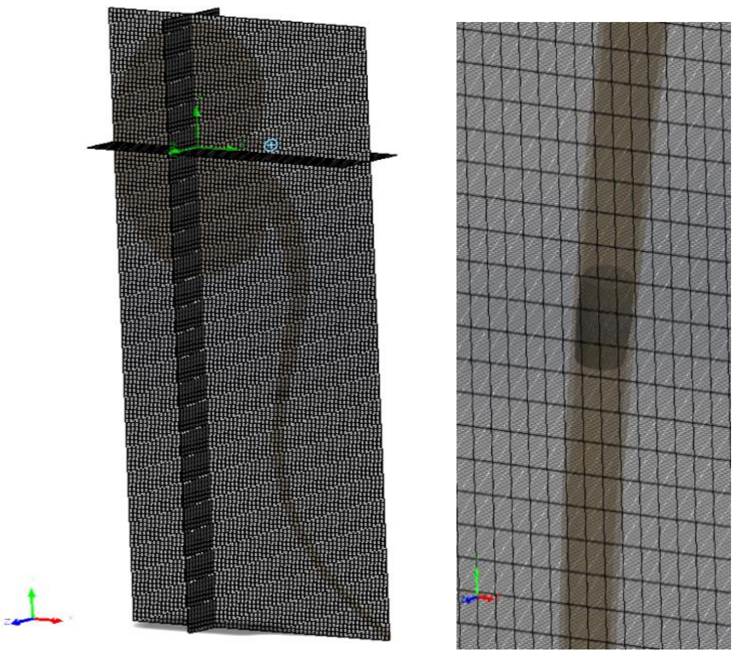

Figure 4. Finite volume model a) Global mesh b) Local mesh

In this model, a 5th-tier tetrahedral network structure is used. Mesh spacings of 2, 3, 4, 5 and 6 were tested for ureteric outlet pressure in laminar flow at average velocity and finally a 5th stage finite volume modeling was found to be suitable for all cases. The total number of elements obtained in this mesh stage was 178,625. The number of nodes is 196,354. It was determined that the effect of the next stratification on the result was not much. This stage was chosen considering the memory-time savings. This assessment is given in Figure 5.

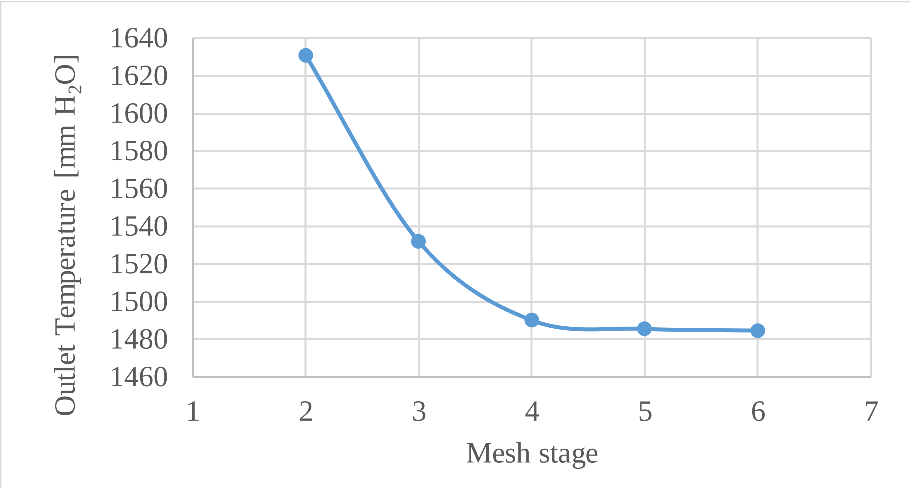

Figure 5. Mesh independence test

3.2. Velocity and Pressure Contours

In the designed model, fluid dynamics is evaluated in terms of velocity, static pressure, dynamic pressure, and differential pressure. Depending on the number of cells in the modeling, the criteria for convergence of the results vary. At the specified analysis settings, the program outputs were obtained after 325 iterations.

As it is understood from the literature, one of the main causes of pain in the kidney region is the formation of high-pressure areas due to obstruction. Contrary to pressure, low or zero fluid velocities occur in these regions due to insufficient flow. These regions are given in Figure 6a and Figure 6b for pressure and velocity, respectively. The blue contours represent the minimum (zero) values, while the red contours represent the maximum velocity values. The trend shows a steady increase in urine velocity across the ureter from the entrance to the exit of the occlusion zone due to the natural narrowing of the diameter. Drinking water or consuming fluids causes an increase in the amount of fluid in the kidney. The increase in pain with the effect of high pressure also forces the ureteral stone to move towards the exit. At what pressure and how much the stone will move is not determined as a result of this analysis. However, it helps to put forward healthy ideas about diagnosis and treatment.

Streamlines and contour plots show decreased urine output in response to larger contraction magnitudes. It can be seen from the flow trajectory lines given in Figure 7 that the total flow in the congested region has decreased significantly. The values given here are the calculation results at 10% permeability (almost non-occlusion) where good permeability is achieved.

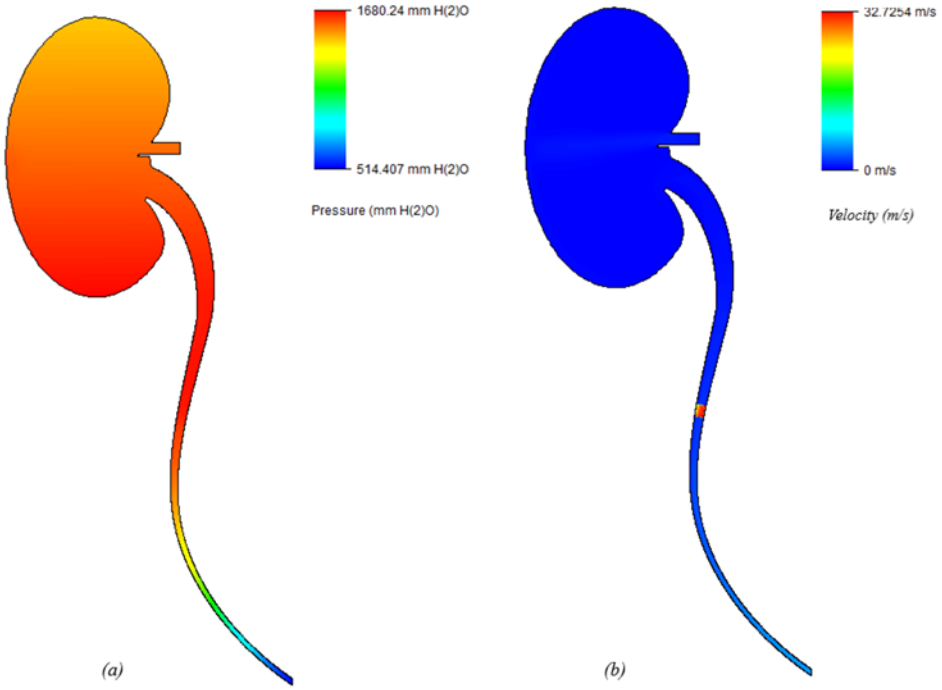

Figure 6. a) Pressure and b) Velocity Contours

Figure 7.a shows that the pressure begins to increase in the lower regions of the kidney model. It is clear that at higher flow inlet rates a high-pressure environment will be created throughout the entire kidney. Figure 7b shows the pattern in which low velocities occur as opposed to pressure. Although the velocity is relatively higher in porous media, it will not significantly affect the continuity of the flow.

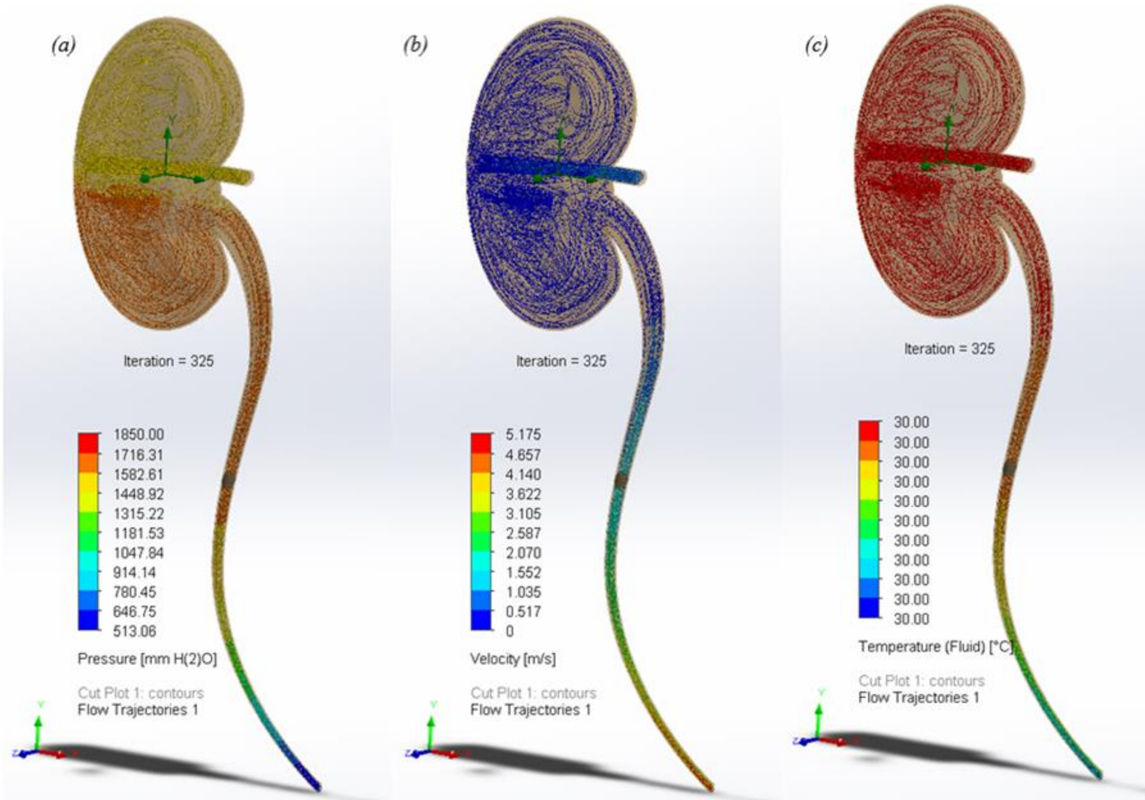

Figure 7. Flow trajectories a) Pressure b) Velocity c) Temperature

In addition, it should be understood from Figure 7.c that different temperature zones can be formed only by the effect of flow. Since the fluid produced in the kidney is closer to the outlet, it is expected to be warmer than the ureter outlet. This situation should be examined in detail by considering the thermal energy of the produced urine and the heat transfer interactions of the system. Note that it is emphasized here that only modeling simulation can be done.

The kidney stone simulation, modeled as a porous medium, gives information about the change of flow properties in channel narrowing with permeability condition. Flow trajectories for pressure and velocity in this region are given in Figures 8.a and 8.b, respectively. It is difficult to predict the movement of true ureteral stones, which often have different surface roughness properties. However, different permeability conditions are expected to occur with the effect of channel cross-section and rotation as it progresses along the channel.

It is understood that with the increase of permeability, the pressure in the kidney and ureter and thus the pressure-related pain may decrease. On the other hand, it can be interpreted that the decrease in pressure will decrease the magnitude of the forces that have a repulsive effect on the stone and adversely affect the dropping process.

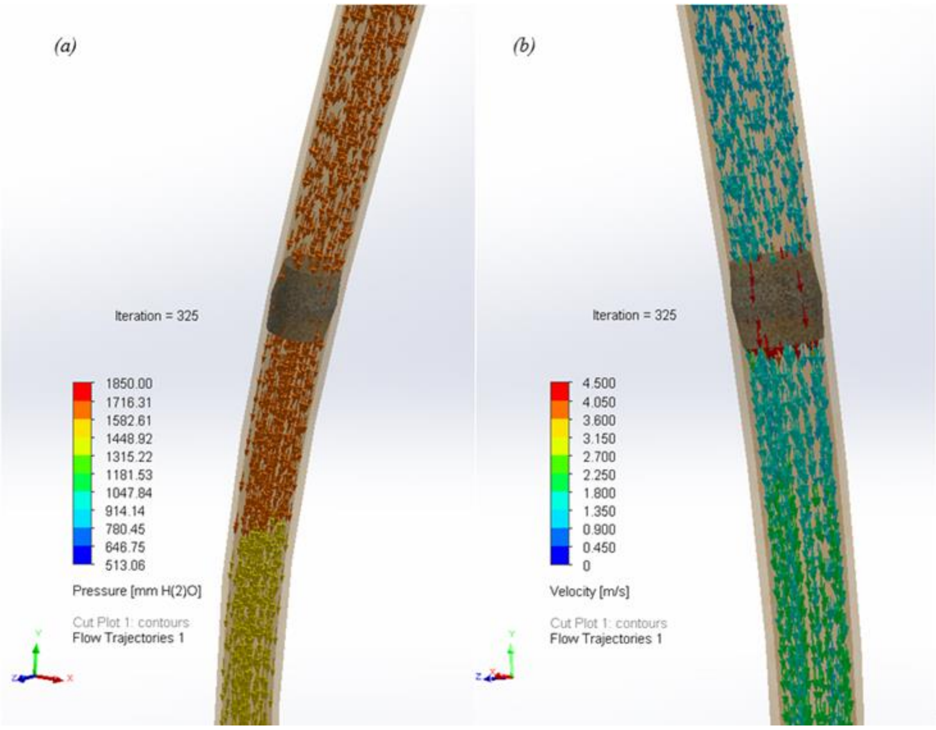

Figure 8. Occlusion (stone) zone flow trajectories a) Pressure b) Velocity

The velocity, pressure and temperature contours in the congestion zone are given in Figure 9. The presence of fluid flow is visible in all contours. Pressure drop in this region is accompanied by high seepage flows. The temperature contours have the potential to change according to the duct heat transfer conditions. This situation needs to be examined separately according to body mechanisms.

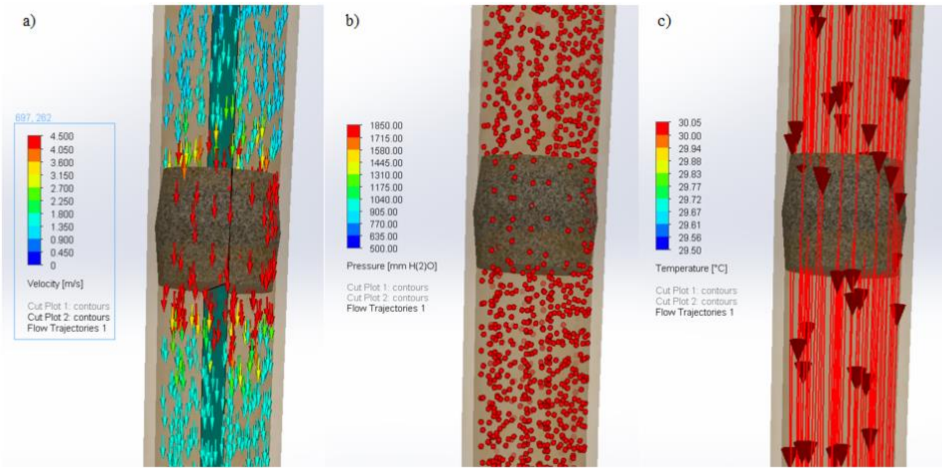

Figure 9. Contours in Congestion Zone a) Velocity b) Pressure c) Temperature

3.3. Effect of Inlet Conditions and Permeability

The numerical pressure difference values obtained from these models, especially focusing on the flow in the inlet, constricted and outlet regions, are given in Figure 10. In the channel flow, the direct effects of the inlet and outlet region on the flow are avoided and continuous flow conditions are provided. In the congested region, there is a continuous flow situation like seepage. The permeability values determined to indicate the severity of the blockage significantly affect the flow. The values presented in Figure 9 are representative approximations based on the model created, average permeability and assumptions made.

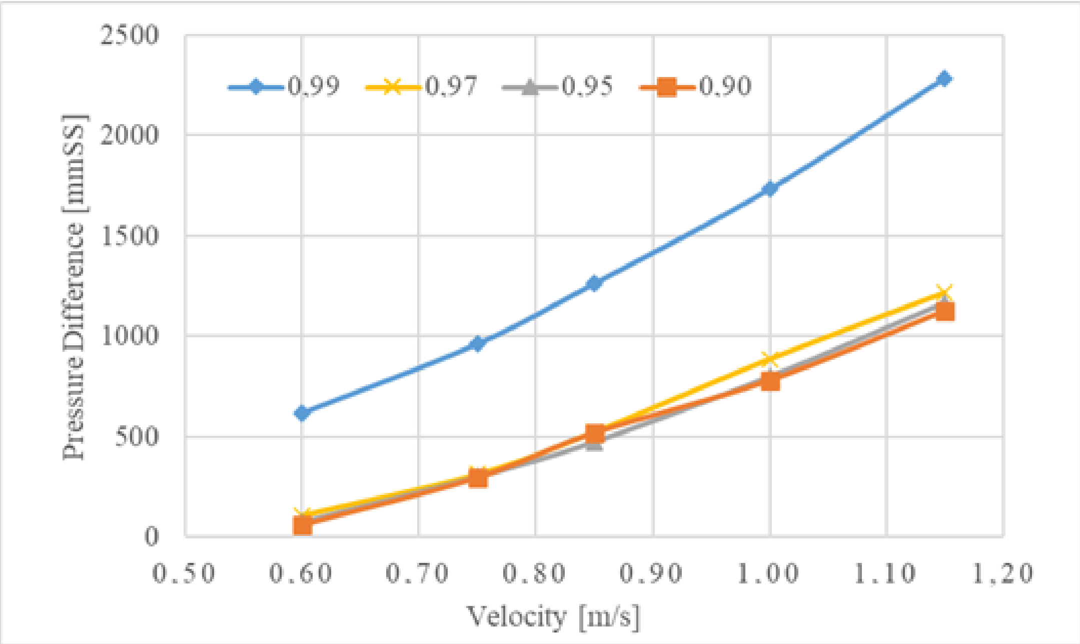

Figure 10. Effect of permeability on pressure difference according to input conditions

Increasing the inlet velocity causes an increase in the pressure difference for all roughness values. However, it is not possible to talk about a continuous flow for the case of complete occlusion. Here, the values obtained for the states from 99% transmittance to 60% are compared. The highest permeability is a flow condition with almost no clogging and, as expected, the highest-pressure difference is for this value.

4. Conclusions and Recommendations

Applications in which fluid and flow conditions are evaluated are within the working areas of engineers. Improving flow and fluid conditions by performing numerical and experimental studies are the focus points for such applications. Blood and urine flow, which are the subjects of two health fields, also attract the attention of engineers in terms of flow and flow geometries. It is expected that these different professional groups will cooperate in determining the materials and methods necessary for the prevention or treatment of diseases, especially in the protection of human health. The continuous development of computational fluid mechanics analytical tools gives good results in the analysis of most real flow phenomena. The use of these benefits for the protection of human health is an inevitable necessity of science. In this study, the issue of the removal of stones produced in the kidney or canal from the body as a result of their movement along the ureteral canal is discussed. As a basic approach, it is thought that solid formation causing obstruction at any point of the ureteral canal will influence the pressure increase in the canal and kidney. An occlusion zone that allows partial flow in an average narrow section of the ureteral canal was considered. Increasing the inlet velocity introduced into the system from 0.6 m/s to 1.2 m/s to represent water consumption and thus urine production ensures an increase in pressure difference for all permeabilities included in the analysis. The situation where this difference is greatest is for 0.99 permeability at 2257 mmH_2O. Thus, the effect of permeability and increased fluid amount on pressure, which is thought to be one of the causes of pain, was simulated in the stone removal process. As a result, the velocity, pressure, and temperature effects of the flow region at different permeability allowing flow in any section of the ureteral canal were revealed. It was ensured that the urine produced in the kidney could be evaluated as the continuous flow condition introduced to the kidney. For example, it has been interpreted that increased fluid consumption will increase the continuous flow rate in this region, and accordingly, where high pressure regions may occur. Thanks to this study, it was thought that it would be useful for evaluations that can only be made in the diagnosis and treatment of flow and fluid conditions. A more realistic modeling of the renal environment and computerized analysis taking into account the stretching ability of the ureteral blood were recommended.

Authors' Contributions

The author contributed one hundred percent to the study.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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